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475153  
**Computed Faraday Rotation During  
Sporadic-E Propagation**

**by**

**T. A. Croft**

**October 1965**

**Technical Report No. 113**

**Prepared under**

**Office of Naval Research Contract**

**Nonr-225(64), NR 088 019, and**

**Advanced Research Projects Agency ARPA Order 196-65**

**RADIOSCIENCE LABORATORY**  
**STANFORD ELECTRONICS LABORATORIES**

**STANFORD UNIVERSITY • STANFORD, CALIFORNIA**



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Radioscience Laboratory  
Stanford Electronics Laboratories  
Stanford University                      Stanford, California

### ABSTRACT

Because they exist in thin sheets, sporadic-E layers tend to affect radio waves in a manner which is very similar to the reflection of light waves by a mirror. A question then arises concerning the presence or absence of Faraday rotation of the plane of polarization of the electromagnetic field when it is propagated from ground to ground by means of sporadic-E "reflection." This paper presents the results of a comprehensive set of digital computer calculations designed to reveal the number of turns which should theoretically be expected in such circumstances. Since the answers are strongly affected by the ionization density underneath the sporadic-E layer, this "D-region ionization" was chosen with some care. The answer also depends markedly on whether the radio wave is refracted within a sporadic-E layer or whether it is reflected off the layer by virtue of an abrupt change in the index of refraction. Computed results are given for both of these cases, since the true nature of this mechanism is not presently known.

Results show that rotation is greatest at low frequencies, low take-off angles, and geomagnetic azimuths near 0 deg, and also that rotation is more marked in the daytime than at night. None of these qualitative results are new, but the quantitative measures of the relative importance, as given herein, have not been described before.

It is seen that significant Faraday rotation occurs throughout the high-frequency band and also into the vhf band, provided the azimuth is not too nearly transverse to the field. However, for east-west vhf transmission, the Faraday rotation becomes negligible.



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## 1. INTRODUCTION

When compared to the relatively gentle refraction which takes place in the "normal" ionosphere, the sharp bending of raypaths which encounter sporadic-E layers appears almost like a reflection off a mirror. Because the raypaths are nearly straight during their transit from the ground to the ionosphere and back, many experimental records of sporadic-E encounters can be adequately explained by postulating a mirror and completely neglecting all effects due to electrons beneath the mirror.

An important question has arisen in this context concerning the number of Faraday revolutions executed by a raypath as it travels from a transmitter to a sporadic-E patch and reflects back to a receiver on the ground. Differing opinions have been expressed at times when communication-system configurations have been dependent on the answer to these questions.

This paper presents a comprehensive system of computer calculations designed to simulate the action of a ray as it undergoes Faraday rotation during a traverse from the ground transmitter to the ionosphere and back to the ground. In the calculation, reasonable electron densities were used below the sporadic-E layer to simulate a daytime or nighttime D layer. The  $E_s$  layers themselves were simulated by a graded shell of moderate density approximately 1 km thick, because such a structure has been detected when rocket probes have passed through sporadic-E layers [Ref. 1]. Results computed at a variety of frequencies, takeoff angles, and magnetic azimuths show the number of Faraday turns undergone by raypaths in this manner. It is seen that the number of turns is maximized at low frequencies, at low takeoff angles, at azimuths near alignment with the field, and in the daytime. None of these answers are surprising or new, but the absolute magnitudes of the rotation angles given here permit, for the first time, an accurate quantitative measure of the number of turns and how this number varies as a function of the azimuth, time of day, frequency, or takeoff angle.

The number of calculated turns depends markedly on whether the action of the sporadic-E layer is one of refraction (as it is in the "normal" ionosphere) or one of reflection due to a change in electron density in

the space of very few wavelengths. More Faraday turns are undergone in the former case than in the latter; but even when a mirror analogy is used at a height of 110 km, it will be seen that considerable Faraday rotation takes place at all frequencies of 30 Mc or below.

It is hoped that these calculations will facilitate the interpretation of experimental data or help in the planning of experiments to resolve the question. From these calculations alone, it is probably safe to conclude that a rotation of 10 deg or less occurs only in a special case of vhf east-west propagation and is not representative of the average situation. Thus, one would generally be ill-advised to plan a system based on an assumption that the transmitted and received polarization would always be identical.

## II. METHOD OF CALCULATION

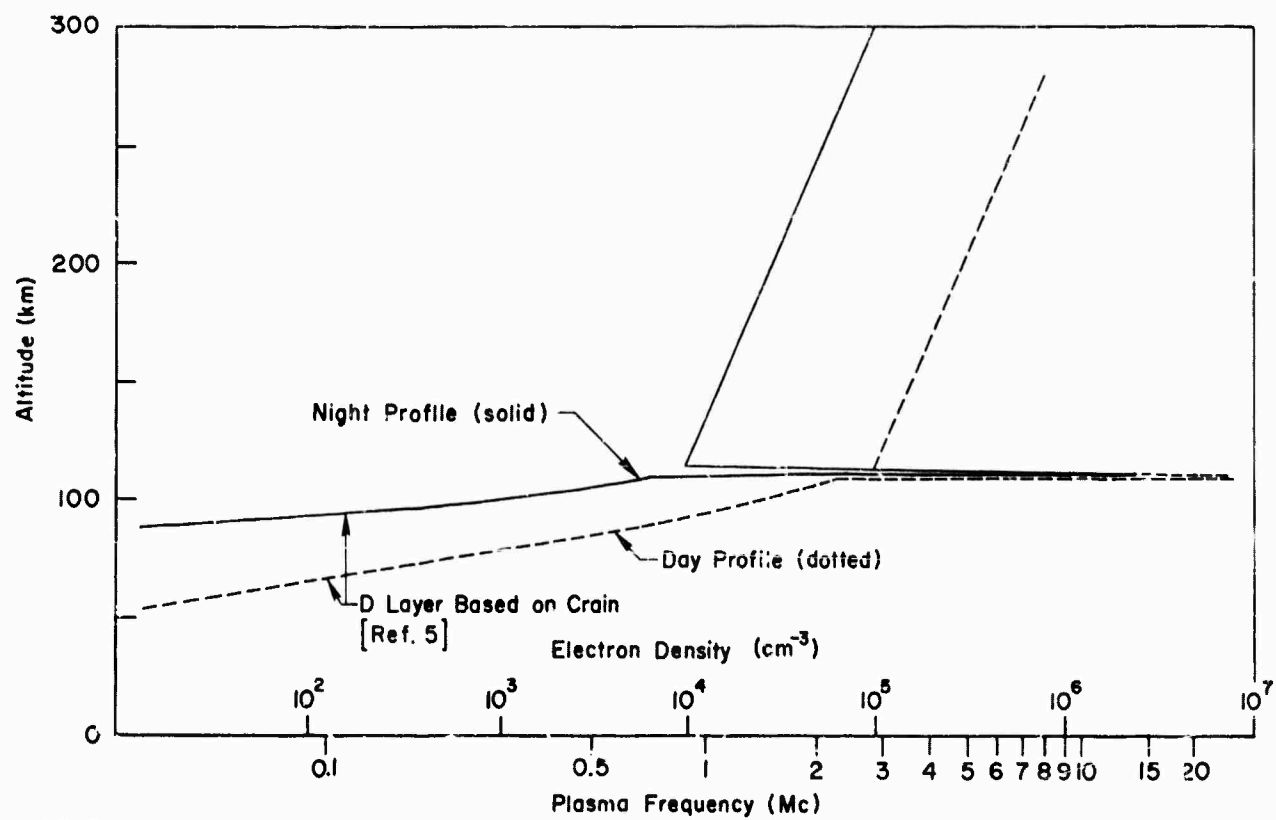
Basically, the computer program was a modified version of a Snell's-law raytracing program described in Technical Report 82, entitled "A Fast, Versatile Ray-Tracing Program for IBM 7090 Digital Computers" [Ref. 2]. This program calculates the progress of a ray through the ionosphere as a series of short straight-line segments, but the calculation is carried out so often that the path of the ray closely approximates the actual curved path followed by radio energy in the real ionosphere. For the Faraday-rotation calculation, the quasi-longitudinal (QL) approximation was used by means of a formula previously given by Garriott [Ref. 3]. It has been shown [Ref. 4] that the QL approximation is quite good, even when the ray trajectory is very nearly perpendicular to the magnetic field, so long as the calculation involves only the Faraday rotation of the ray. Similarly, in the latter reference, it was pointed out that the most practical way to calculate Faraday rotation (at frequencies such as those of interest in this paper) involves the calculation of a ray-path without a magnetic field. Thus, while Faraday rotation is due to the interaction of ordinary and extraordinary waves, the total effect can be evaluated by calculating a no-field raypath and then using a QL expression for the total Faraday rotation along each segment of the raypath.

The ionosphere was modeled by a sampled-data function giving electron density  $N$  vs height  $H$ ; a listing of this function is given in Table 1. This electron density is plotted on Fig. 1 as a function of height. It is seen that the D-region ionization is stronger in daytime than it is at night. The actual distribution of electrons was obtained from a paper by Crain [Ref. 5]. After several years of experience in using Crain's D region, the author feels that his approximation is much smoother than the true distribution but it seems to be about the best that can be expected from a general-purpose model. True variations from day to day will not follow his curves exactly, but they will seldom be very far off. For example, the difference between the day curve and the night curve is greater than the difference between a true experimental curve and these approximations. This is an important point to keep in mind, because the

actual distribution of electrons in the D region will be seen to play a major role in Faraday rotation of rays which reflect off sporadic E.

TABLE 1. PRINTOUT OF IONOSPHERES

Height (km)	Electron Density (cm <sup>-3</sup> )	Height (km)	Electron Density (cm <sup>-3</sup> )	Height (km)	Electron Density (cm <sup>-3</sup> )
<u>DAY</u>		<u>DAY</u>		<u>NIGHT</u>	
53.00	11.89	88.00	4446.08	87.00	8.18
54.00	14.15	89.00	5165.07	88.00	13.32
55.00	16.85	90.00	5996.55	89.00	21.37
56.00	20.08	91.00	6951.21	90.00	33.73
57.00	23.95	92.00	8031.45	91.00	52.41
58.00	28.56	93.00	9249.07	92.00	80.08
59.00	34.07	94.00	10615.97	93.00	120.32
60.00	40.64	95.00	12154.56	94.00	177.64
61.00	48.49	96.00	13888.94	95.00	257.62
62.00	57.84	97.00	15829.58	96.00	366.84
63.00	68.97	98.00	17973.58	97.00	512.66
64.00	82.11	99.00	20351.41	98.00	700.51
65.00	97.63	100.00	22967.13	99.00	939.76
66.00	116.00	101.00	25848.88	100.00	1237.45
67.00	137.85	102.00	29048.47	101.00	1596.72
68.00	163.98	103.00	32514.96	102.00	2017.74
69.00	195.13	104.00	36260.33	103.00	2492.83
70.00	232.13	105.00	40273.18	104.00	3010.88
71.00	275.65	106.00	44559.10	105.00	3564.68
72.00	327.14	107.00	49192.86	106.00	4151.33
73.00	388.30	108.00	54258.96	107.00	4760.41
74.00	461.78	109.00	59598.03	108.00	5399.31
75.00	548.86	110.00	65307.71	109.00	6063.35
76.00	650.02	110.20	1.00E+05	110.00	6735.40
77.00	767.45	110.40	2.00E+05	110.20	1.00E+04
78.00	905.11	110.60	4.00E+05	110.40	2.00E+04
79.00	1063.45	110.80	8.00E+05	110.60	4.00E+04
80.00	1261.67	111.00	1.60E+06	110.80	8.00E+04
81.00	1488.22	111.20	3.20E+06	111.00	1.60E+05
82.00	1749.46	111.40	6.40E+06	111.20	3.20E+05
83.00	2052.68	111.60	1.28E+07	111.40	6.40E+05
84.00	2404.29	111.80	2.56E+07	111.60	1.28E+06
85.00	2812.24	112.00	2.56E+07	111.80	2.56E+06
86.00	3285.61	114.00	1.00E+05	112.00	2.56E+06
87.00	3824.39	300.00	1.00E+06	114.00	1.00E+04
				300.00	1.00E+05



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FIG. 1. ELECTRON DENSITY PROFILES USED FOR RAYTRACING.

### III. SPORADIC-E REFLECTION MECHANISMS

There are a number of possible mechanisms for reflection off sporadic E, although current scientific thinking on this matter has not led to a meeting of the minds. (Several views are summarized in Ref. 6.) Therefore, we must calculate for the case of refraction as in a normal ionospheric layer, and also we must calculate for reflection due to a sharp discontinuity. In the latter case, the ray may bend without undergoing any Faraday rotation whatsoever, because the sporadic-E path looks like a mirror to the wave which encounters it. (The phase might reverse 180 deg, but this possibility is inconsequential in the present context.) In the case where the ray traverses the sporadic-E region for a few hundreds of meters, the Faraday rotation of the ray while it is actually in the sporadic-E layer is in some cases a significant proportion of the total rotation of the ray. Therefore, the results given here will include both possibilities.

Reference 6 describes a number of approaches to the solution of the wave equation for the boundary conditions which exist in the presence of a thin sporadic-E layer. As is usually the case, the results of these calculations are presented on graphs which are parametric in some measure of the thickness of the sporadic-E layer. For very thin layers, not much energy is reflected, and the layer looks semitransparent. However, as the layers get thicker, a higher and higher percentage of the impinging energy is reflected off the layer. Finally, when the layer achieves sufficient thickness, the refraction mechanism takes over, and the ray approximations which invoke refraction become closer to the true solution.

In Ref. 6 it will be seen that the ray approximation is valid for layers which are thicker than approximately 0.1 km. The exact magnitude of the necessary thickness is a function of the radio frequency, but for the frequencies of interest here, it appears that layers thicker than 0.1 km reflect essentially all the energy so that the ray approximation gives a valid answer.

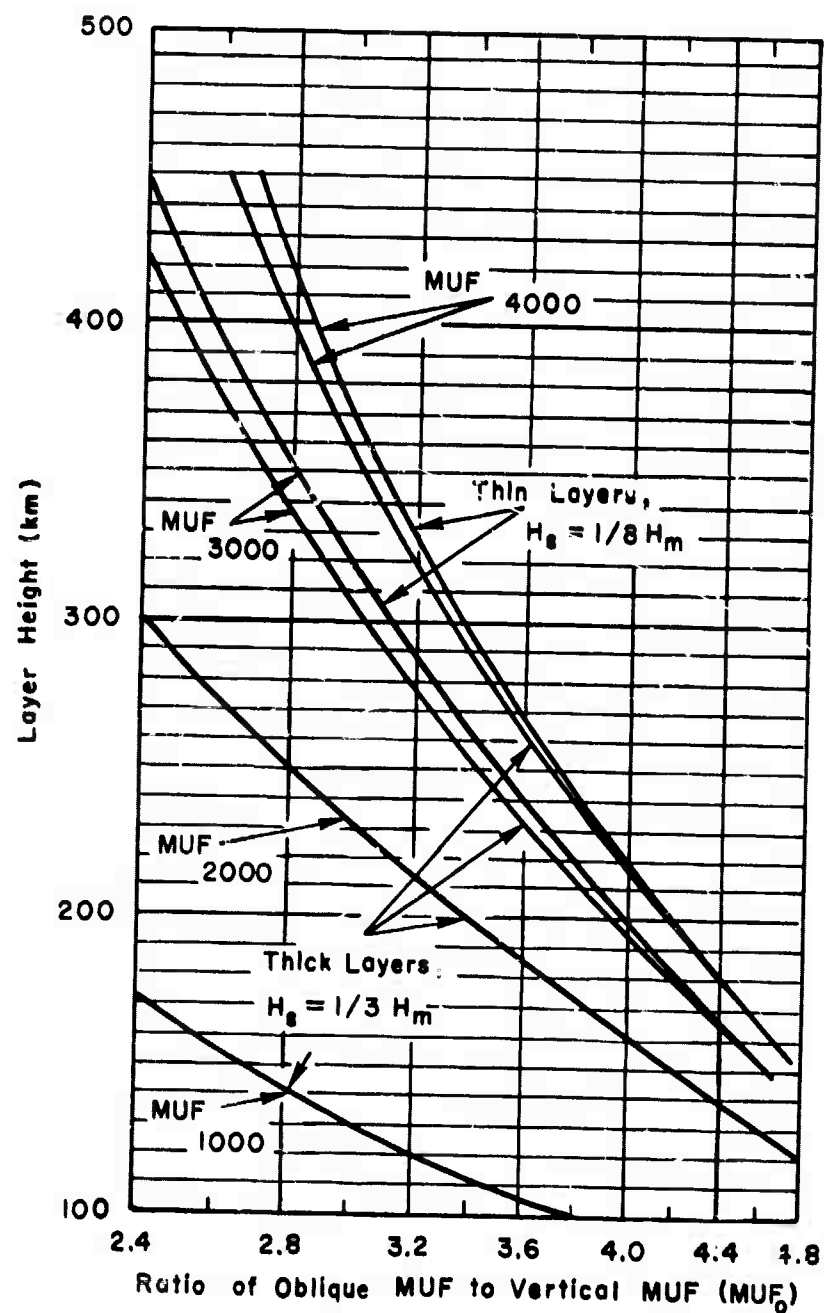
Some of the best information available concerning the thickness of sporadic-E layers has been obtained by rocket probes which measure electron

density as they travel through these layers. Examples of such measurements are given in Refs. 7 and 8. In both of these rocket measurements, the thickness of the sporadic-E layer was of the order of a kilometer, indicating that radio energy would be totally reflected at all frequencies below the plasma frequency of the layer, as corrected by the Secant law. More recent data presented at the 1965 fall URSI meeting is in agreement with this reasoning [Ref. 9].

One word of caution for readers of Ref. 6: the scales chosen for the drawings are awkward and inconsistent, so care must be taken in comparing the various figures. For example, on one page two figures are shown, one above the other, giving results computed by two different authors. The reader is supposed to compare these results by comparing the two figures. However, the horizontal scale of one of the two figures is the inverse square of the horizontal scale on the other figure, for no apparent reason.

It seems reasonable to assume that reflection off sporadic E is predominately a refraction mechanism through a layer approximately a kilometer thick. This thickness exceeds the wavelength of the radio rays of interest in this study, and the ionization discontinuity is not sufficiently sharp to produce a significant reflection. However, because of the low altitude of the layer, the Secant law plays a very strong part in permitting refraction of considerably higher frequencies than can be bent by ionospheric layers at higher altitudes. This phenomenon is shown most strikingly in Fig. 2 where the maximum usable frequency (MUF) is compared to the vertical-incidence critical frequency for a number of Chapman layers as a function of their height above the earth's surface. Both thick and thin layers have been used. In this regard it should be explained that a thick layer has been arbitrarily defined as having a scale height  $H_s$  equal to one-third the height of the layer  $H_m$ , where  $H_m$  is defined at the maximum electron density. A thin layer has a scale height only one-eighth of the height of the layer, so when plotted as a function of height, the electron density distribution appears much thinner and almost like a parabolic layer.



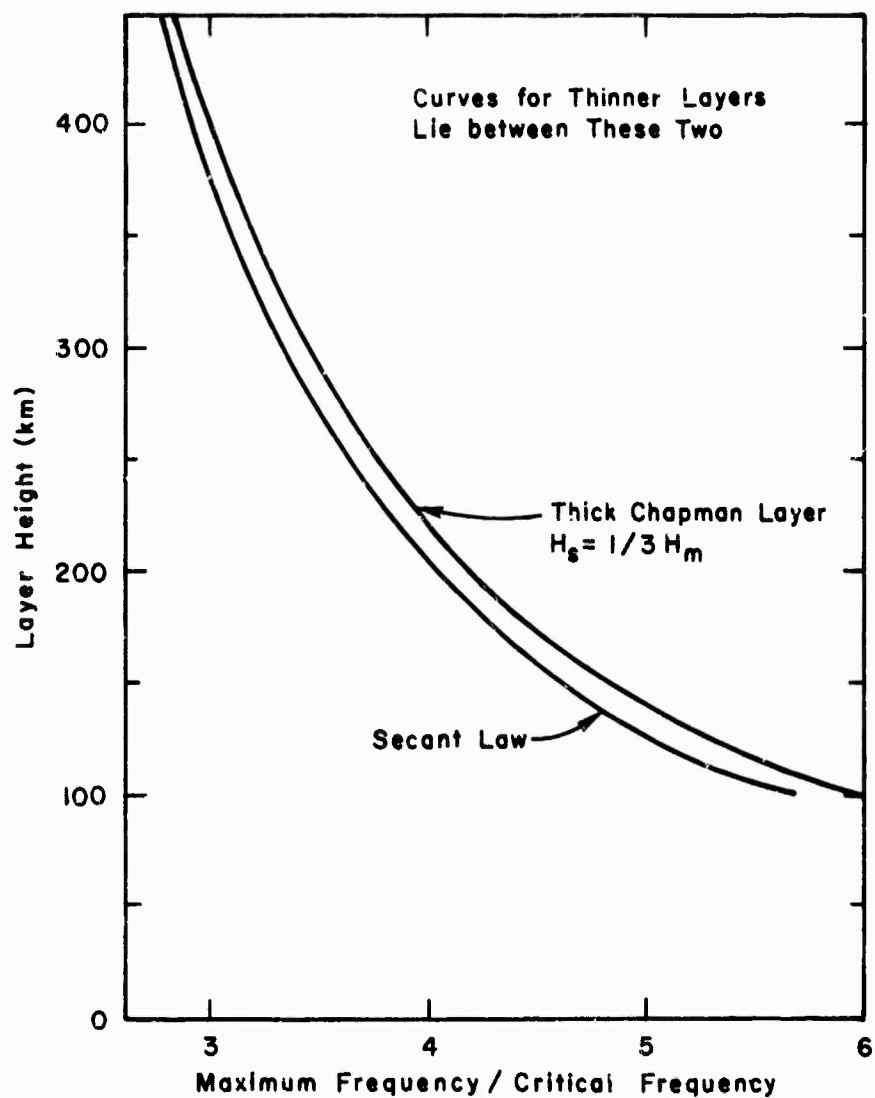


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FIG. 2. MUF RATIOS FOR VARIOUS SINGLE-LAYER IONOSPHERES.

Figure 3 points up this Secant-law effect more strikingly. Here is plotted the ratio of the maximum frequency which can be refracted off a layer as a function of its height. The Secant law is plotted as a single curve, and this might be considered to be the result for a layer of infinite thinness. Another curve is given for a thick Chapman layer in which the scale height is one-third of the maximum height. All results for thinner layers such as sporadic E would lie on curves which were between the two curves given on Fig. 3.

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FIG. 3. MAXIMUM PROPAGATING FREQUENCY FOR SINGLE-LAYER IONOSPHERES.

As a consequence of this reasoning, it can be seen that a sporadic-E layer can refract a ray at frequencies up to six times the vertical-incidence critical frequency of the layer. A sporadic-E layer with a maximum electron density of  $10^6 \text{ cm}^{-3}$  will refract some energy back to the earth for all radio frequencies up to 54 Mc. Thus, for example, it is not surprising that sporadic-E traces appear on oblique ionograms at much higher frequencies than the traces for normal (higher) layers.

#### IV. GRAPHICAL PRESENTATION OF THE COMPUTED RESULTS

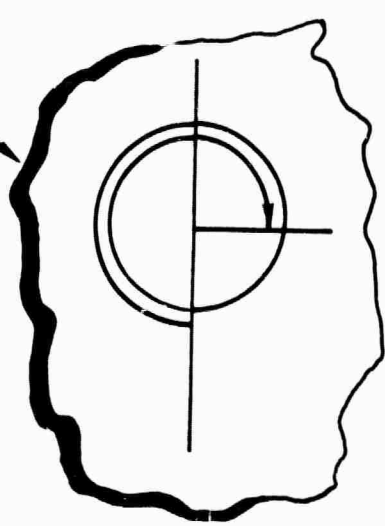
In this section the results of the computation will be given in a graphical format suitable for conveying insight into the nature of the results. Figure 4 shows the meaning of the graphic symbols which will be used in the remainder of this paper. Across the center of the figure is a sketch of the earth with a raypath shown as a twisting ribbon, the turns of which represent the rotation of the plane of polarization of an electromagnetic ray which traverses the raypath. In the example, it can be seen that the total rotation is one and three-quarters turns, or one turn and 270 deg. In this case, if the transmitting antenna were purely vertically polarized, the received signal would be purely horizontally polarized. On the other hand, if the raypath had undergone only one and one-half turns, the received signal would have been vertically polarized. Similarly, if the raypath had undergone one and five-eighths turns (one turn plus 225 deg), then the received signal would have been approximately half vertical and half horizontal in its polarization.

The symbol for this phenomenon is shown at the top of Fig. 4 where a curved-line segment is drawn so that it subtends one turn plus 270 deg at its center. Other typical symbols are shown across the bottom of Fig. 4. Careful examination of these symbols will help the reader to quickly grasp the graphical information which follows.

Using these symbols, the computed results are given on a series of eight displays, Figs. 5a through 5h. Four of these figures apply during daytime and four apply at night. Within each group of four, there is one figure for each of the four geomagnetic azimuths: 10, 30, 50, and 70 deg. For example, Fig. 5c is labeled "Azimuth 30 deg, day ionosphere." This means that the daytime ionospheric model from Fig. 1 was used for the calculation, and the great circle plane in which the calculation took place was inclined at an angle of 30 deg relative to geomagnetic north.

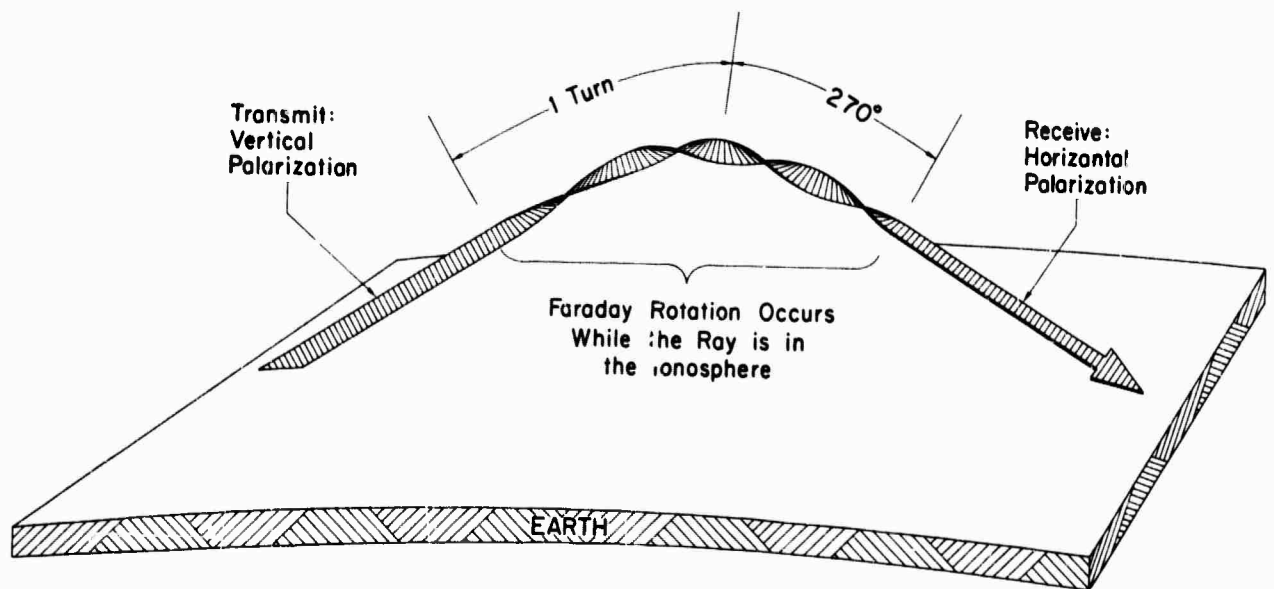
Notice that there is no calculation for azimuth 90 deg. This is because rays thus calculated would undergo no Faraday rotation. More precisely, the accumulated turns of Faraday rotation will be zero. The latter refinement of this statement is necessary because the plane of

Chart Symbol for 1 Turn Plus  $270^\circ$



In the Charts Which Follow, This Symbol

Represents This Phenomenon



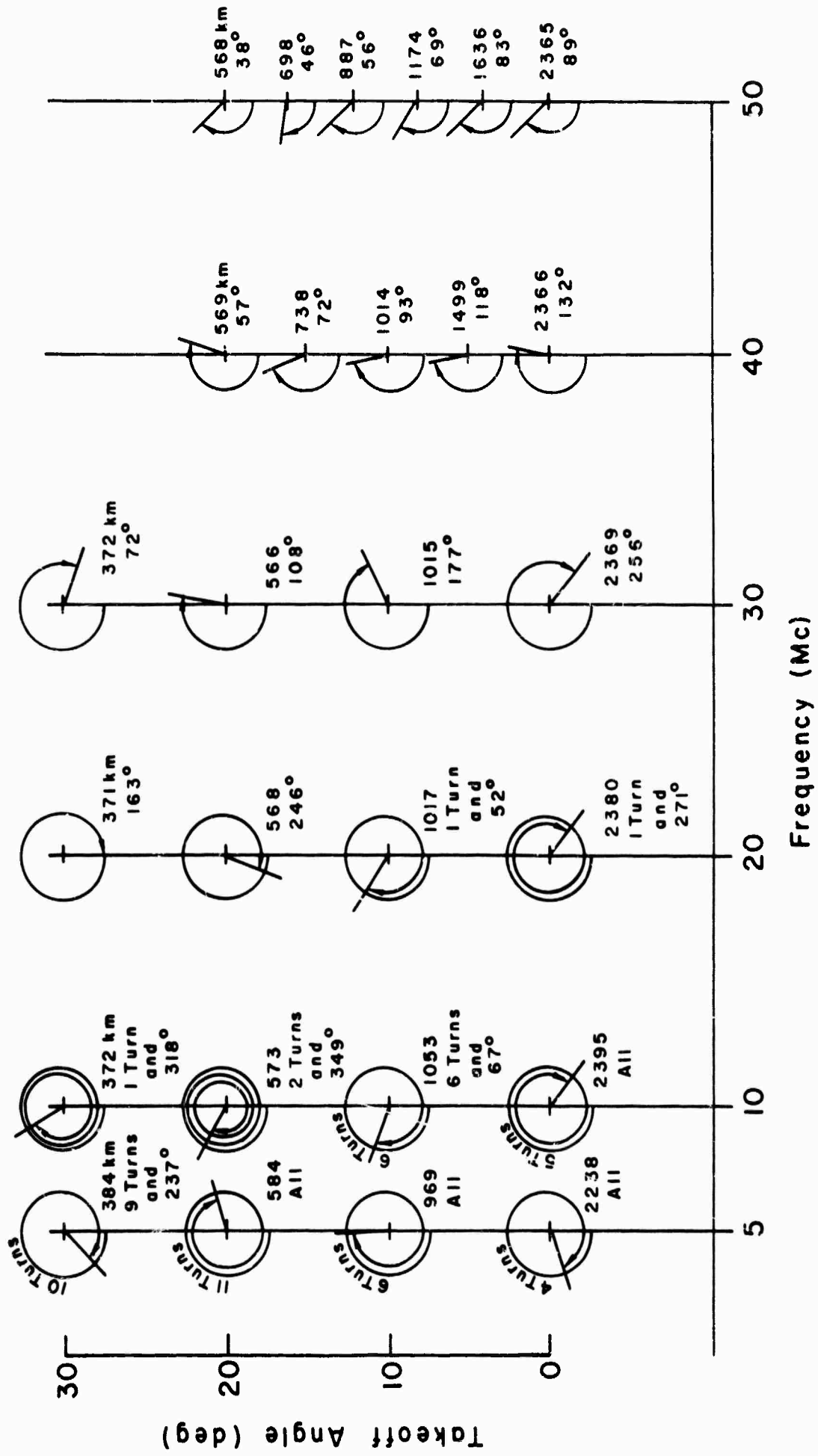
Other Typical Symbols

Amount of Faraday Rotation	10 deg	310 deg	1 Turn Plus 20 deg (380 deg)	10 Turns Plus 280 deg (3880 deg)
Symbol				

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FIG. 4. GRAPHICAL METHOD OF DISPLAYING RESULTS.

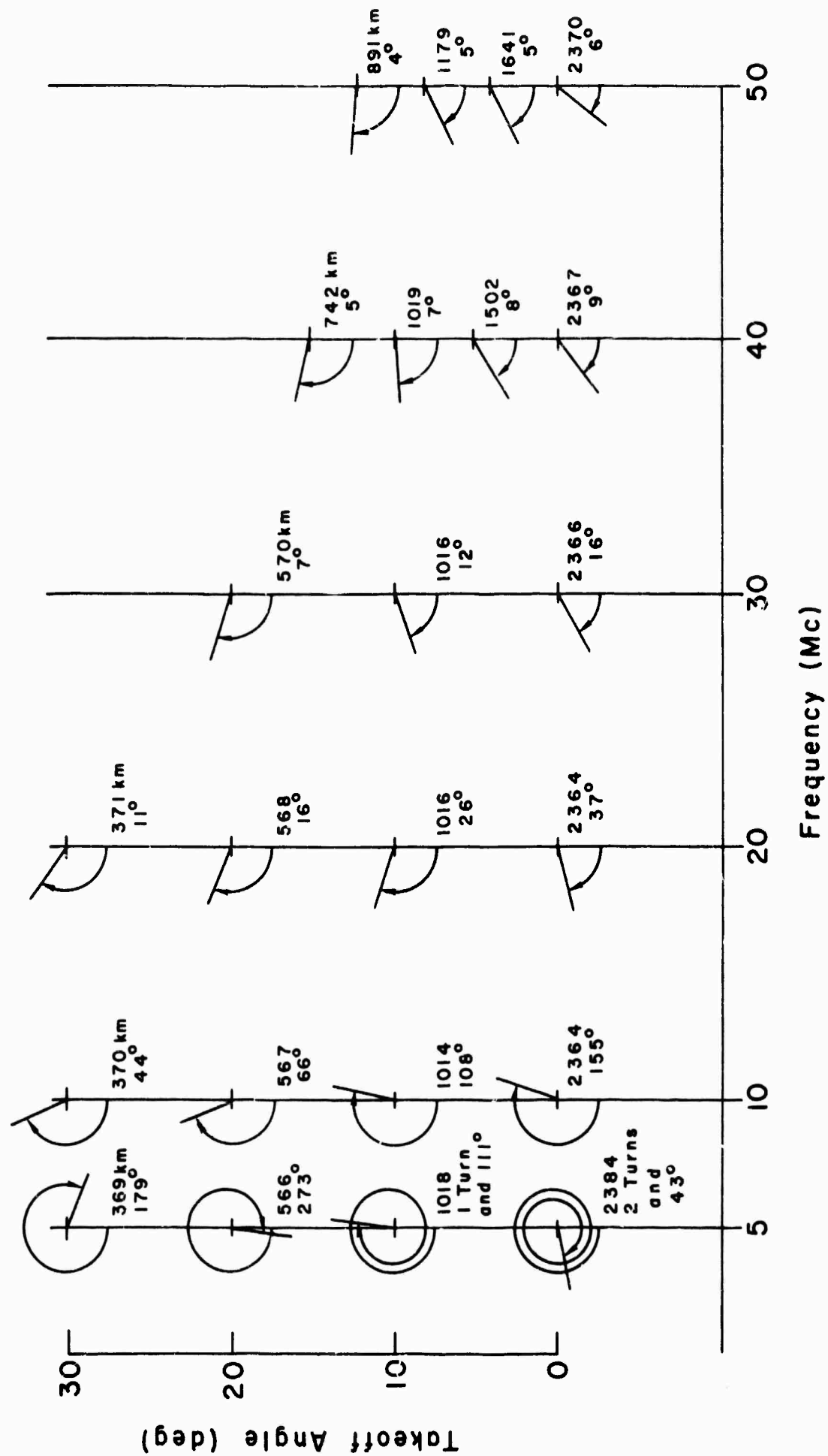
# Azimuth 10°, Day Ionosphere



a. Azimuth 10 deg, day ionosphere

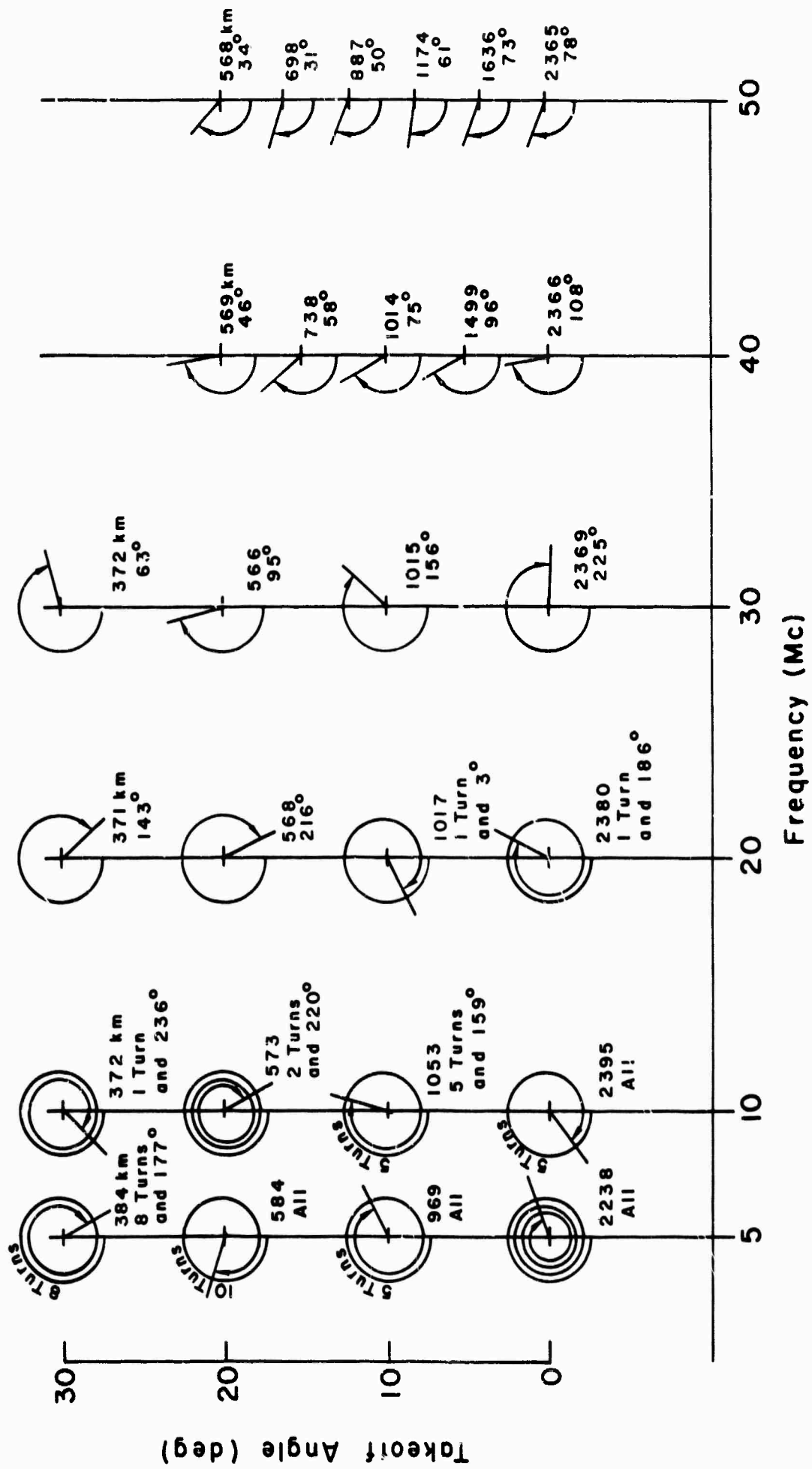
FIG. 5. GRAPHICAL DISPLAY OF RESULTS. Parts (a) through (h) are on pages 12 through 19.

# Azimuth 10°, Night Ionosphere



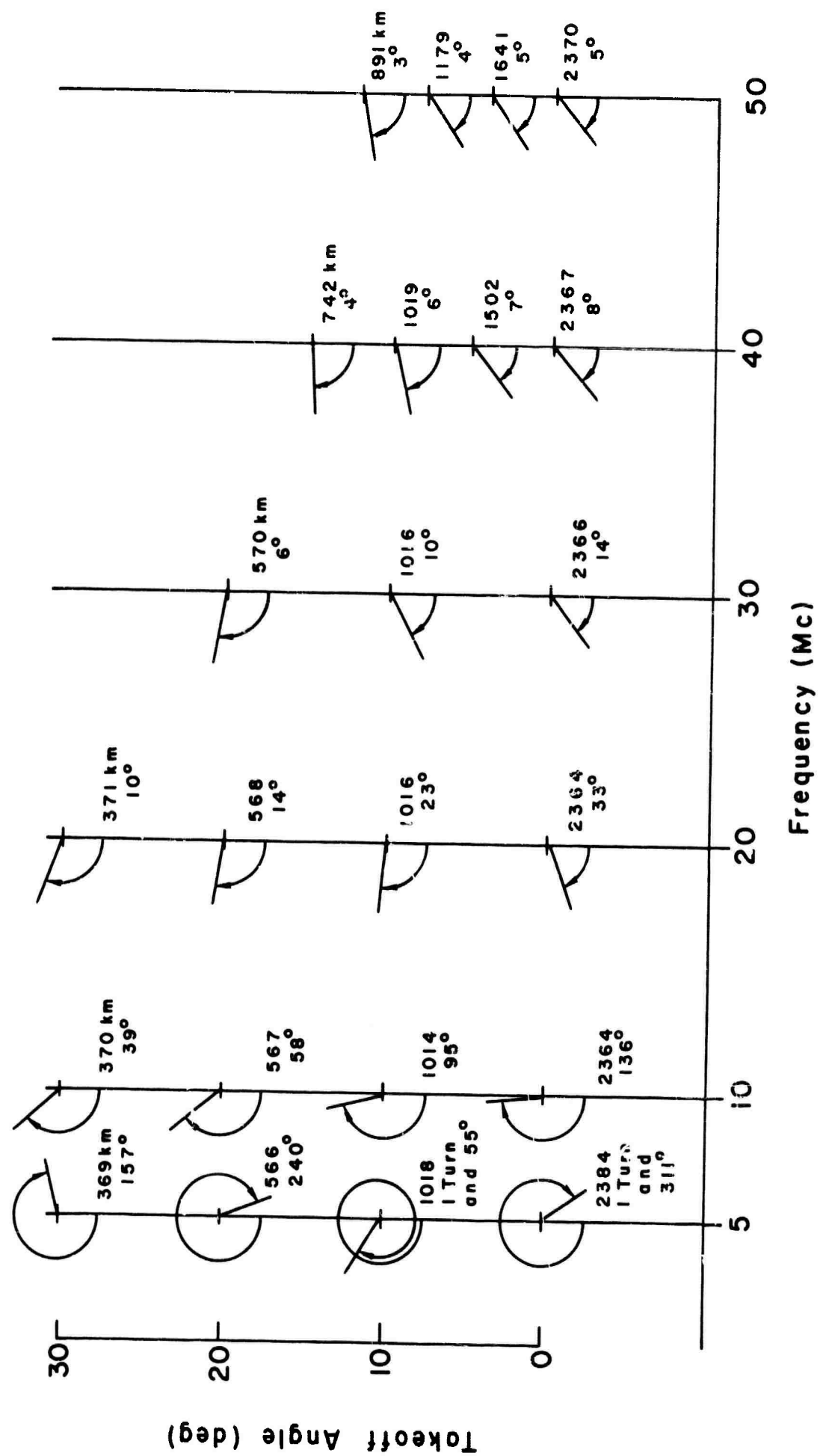
b. Azimuth 10 deg, night ionosphere

# Azimuth 30°, Day Ionosphere



c. Azimuth 30 deg, day ionosphere

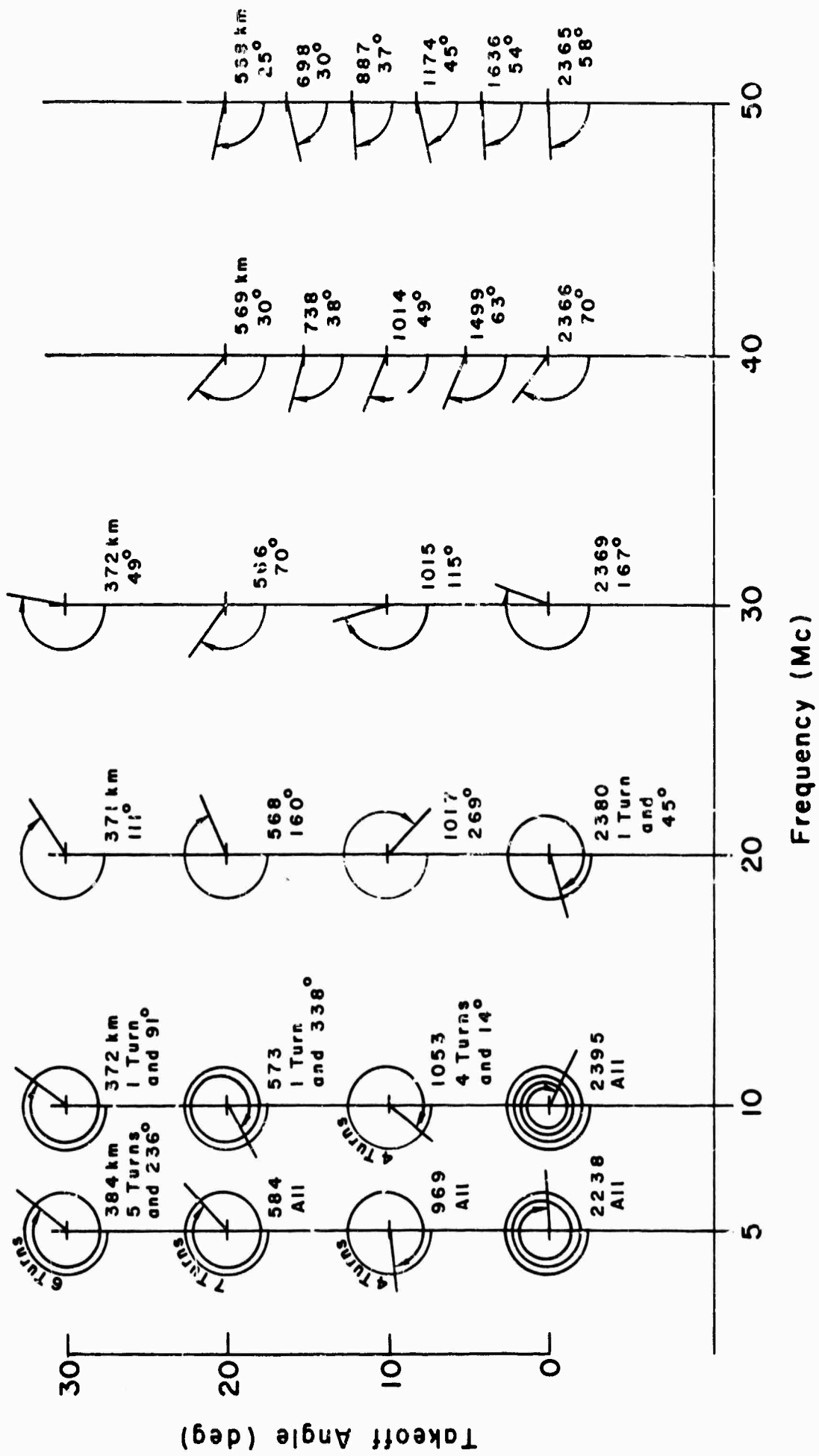
# Azimuth 30°, Night Ionosphere



d. Azimuth 30 deg, night ionosphere

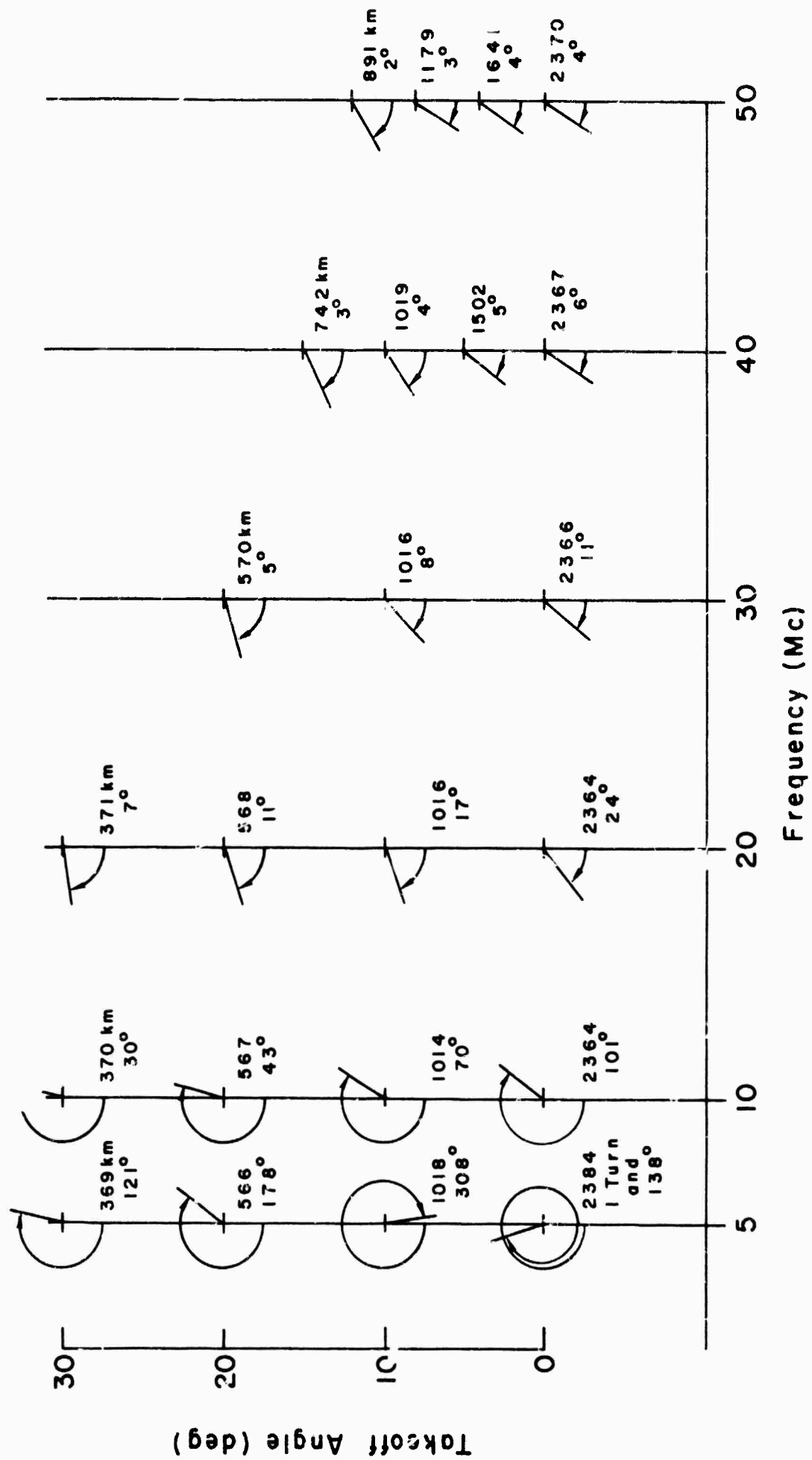


# Azimuth 50°, Day Ionosphere



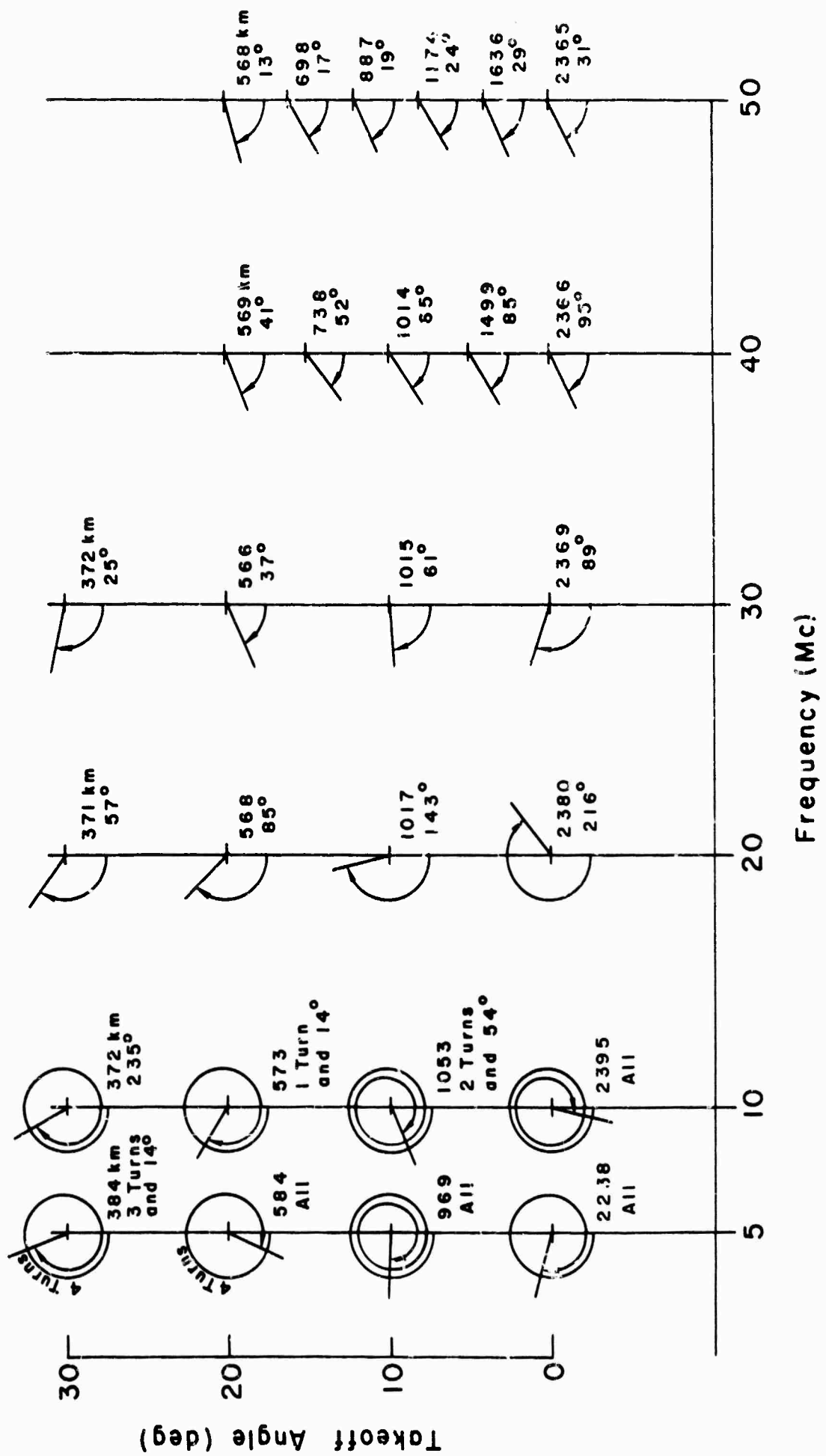
e. Azimuth 50 deg, day ionosphere

# Azimuth 50° Night Ionosphere



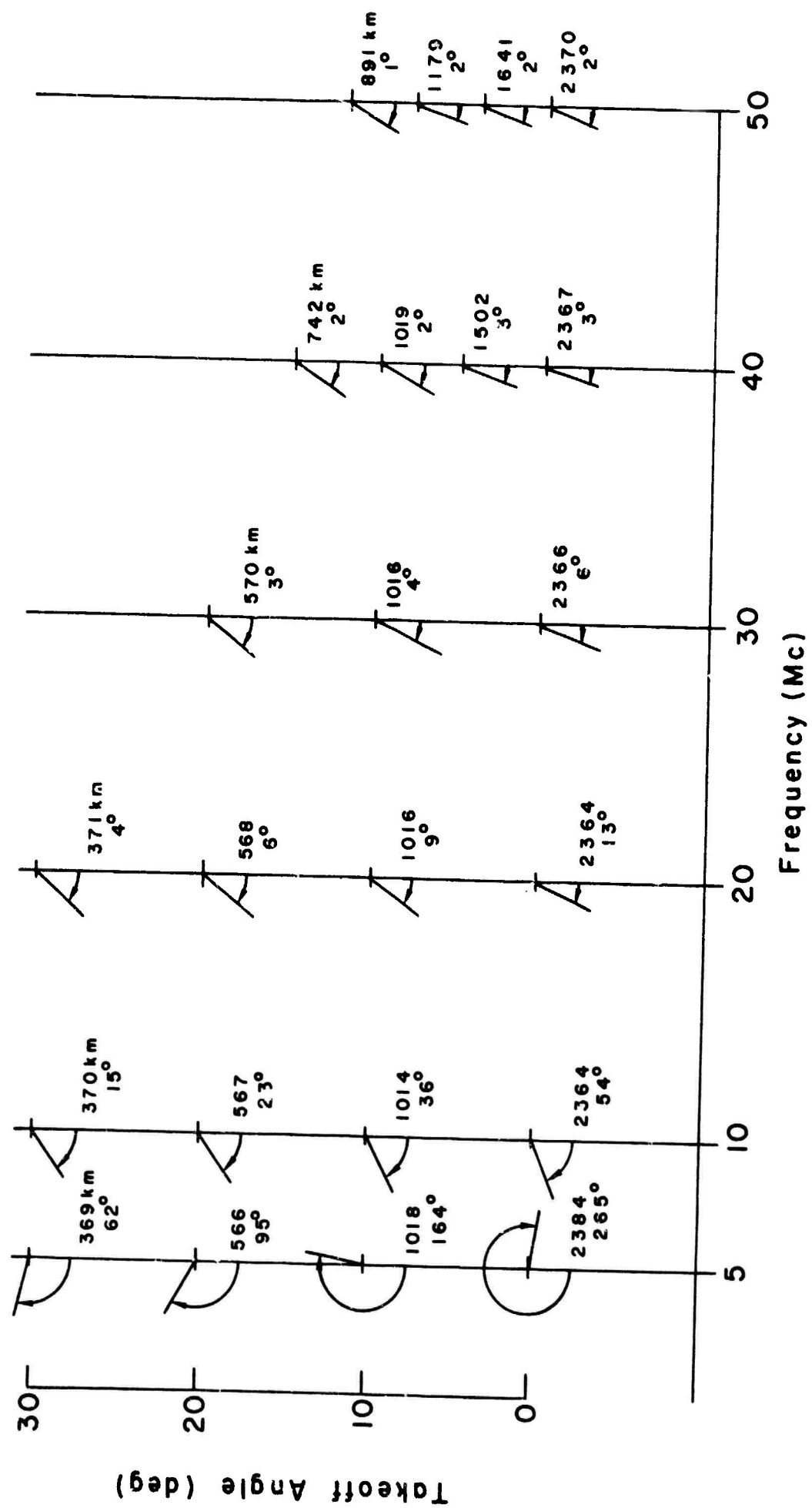
f. Azimuth 50 deg, night ionosphere

# Azimuth 70°, Day Ionosphere



g. Azimuth 70 deg, day ionosphere

# Azimuth 70°, Night Ionosphere



h. Azimuth 70 deg, night ionosphere

polarization will wind up in one direction as the ray ascends to its apogee. However, in descending from the apogee back to the ground, the plane of polarization will unwind by precisely the same amount so that the accumulated turns add to zero.

The layout of each of the eight figures is identical. Along the ordinate is the takeoff angle of the ray, measured from the horizontal. The abscissa is the radio frequency in megacycles. At selected values of these two parameters, digital computer runs were carried out and the results are drawn concentric about the point which lies at the appropriate coordinate position. Thus, for example, reference to Fig. 5a shows that a 30-Mc ray which takes off at 20 deg in the daytime at a 10-deg azimuth will undergo a Faraday rotation of approximately 190 deg.

Notice the two numbers written beside each symbol on Fig. 5. These have the following meaning: The first number is the horizontal ground range traversed by the ray; the second number is the amount of Faraday rotation undergone by the raypath while it is underneath the sporadic-E layer. The purpose of this latter number is to permit a comparison between the Faraday rotation which is caused by the D-layer transition underneath the sporadic-E layer and the rotation while the ray is actually in the sporadic-E layer.

Referring again to the example on Fig. 5a, the 30-Mc, 20-deg ray is seen to have traversed a horizontal distance of 566 km as it underwent a Faraday rotation of approximately 190 deg. However, we also see that only 108 deg of this Faraday rotation took place while the ray was under this sporadic-E layer. Thus, if a reader wishes to take issue with this author's assumption of a refraction mechanism for sporadic-E propagation, the reader can ignore the graphical display and use 108 deg as his answer. The raypath must undergo at least this many turns regardless of the reflection mechanism at the sporadic-E layer.

In some cases, particularly at low frequencies in the daytime, it will be seen that the word "All" is inserted on the drawings in place of the number of turns. This means that the ray under these circumstances refracted off the D layer and never reached the sporadic-E layer. Thus, all turns took place below the sporadic-E layer.

## V. SUMMARY

Using two models of the ionosphere, one for daytime and one for night, results have been computed to show the number of Faraday rotations undergone by a radio wave propagating from the earth to a sporadic-E layer and back to the earth. Calculations were carried out at frequencies between 5 and 50 Mc, at various azimuths relative to the geomagnetic field, and at a number of raypath takeoff angles. In addition, results have been presented not only for the case of refraction off a thick sporadic-E layer but also for the case of reflection off a sharply bounded sporadic-E layer.

It is shown that significant rotation occurs in all cases except when the frequencies are high and the azimuth is near 90 deg. Qualitatively speaking, the Faraday rotation increases at low frequencies, low takeoff angles, and geomagnetic azimuths near 0 deg; also, the rotation is more pronounced in the daytime than at night. However, the primary value of this calculation is in the quantitative measures of the relative significance of these various changes in the propagation conditions.

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<p>Because they exist in thin sheets, sporadic-E layers tend to affect radio waves in a manner which is very similar to the reflection of light waves by a mirror. A question then arises concerning the presence or absence of Faraday rotation of the plane of polarization of the electromagnetic field when it is propagated from ground to ground by means of sporadic-E "reflection." This paper presents the results of a comprehensive set of digital computer calculations designed to reveal the number of turns which should theoretically be expected in such circumstances. Since the answers are strongly affected by the ionization density underneath the sporadic-E layer, this "D-region ionization" was chosen with some care. The answer also depends markedly on whether the radio wave is refracted within a sporadic-E layer or whether it is reflected off the layer by virtue of an abrupt change in the index of refraction. Computed results are given for both of these cases, since the true nature of this mechanism is not presently known. Results show that rotation is greatest at low frequencies, low takeoff angles, and geomagnetic azimuths near 0 deg, and also that rotation is more marked in the daytime than at night. None of these qualitative results are new, but the quantitative measures of the relative importance, as given herein, have not been described before. It is seen that significant Faraday rotation occurs throughout the high-frequency band and also into the vhf band, provided the azimuth is not too nearly transverse to the field. However, for east-west vhf transmission, the Faraday rotation becomes negligible.</p>			



KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
IONOSPHERIC RADIO PROPAGATION COMPUTER PROGRAMMING, Digital IONOSPHERE; E <sub>s</sub> Layer POLARIZATION OF HF RADIO WAVES						

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